Draft version December 8, 2023
Typeset using LATEX default style in AASTeX631

Three Pulsars Discovered in Globular Cluster M15 (NGC 7078) with FAST

Yuxiao Wu,[1] Zhichen Pan,[2,3,4] Lei Qian,[2,3,4] Scott Ransom,[5] BoJun Wang,[2] Zhen Yan,[6] Jintao Luo,[7] Liyun Zhang,[8] Minghui Li,[9] Dejiang Yin,[8] Baoda Li,[8] Yifeng Li,[7] Yinfeng Dai,[8] Yaowei Li,[8] Xinnan Zhang,[9] Tong Liu,[2] and Yu Pan†[1]

[1] *School of Science, Chongqing University of Posts and Telecommunications*
Chongqing, 40000, China
[2] *National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District*
Beijing, 100101, China
[3] *CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences*
Beijing 100101, China
[4] *College of Astronomy and Space Sciences, University of Chinese Academy of Sciences*
Beijing 100049, China
[5] *National Radio Astronomy Observatory, Charlottesville*
VA 22903, USA
[6] *Shanghai Astronomical Observatory, Chinese Academy of Sciences, NO. 80 Nandan Road*
Shanghai, 200030, China
[7] *National Time Service Center, Chinese Academy of Sciences*
Xi'an, 710600, China
[8] *College of Physics, Guizhou University*
Guiyang, 550025, China
[9] *State Key Laboratory of Public Big Data, Guizhou University*
Guiyang, 550025, China

ABSTRACT

We present the discovery of three pulsars in Globular Cluster M15 (NGC 7078) by the Five-hundred-meter Aperture Spherical radio Telescope (FAST). In the three pulsars, PSR J2129+1210J (M15J) is a millisecond pulsar with a spinning period of 11.84 ms and a dispersion measure of 66.68 pc cm^{-3}. Both PSR J2129+1210K and L (M15K and L) are long period pulsars with spinning periods of 1928 ms and 3961 ms, respectively, while M15L is the GC pulsar with the longest spinning period till now. The discoveries of M15K and L support the theory that core-collapsed Globular Clusters may contain partially recycled long period pulsars (Verbunt & Freire 2014). With the same dataset, the timing solutions of M15A to H were updated, and the timing parameter P1 of M15F is different from the previous results, which is approximately $0.027\times10^{-18}ss^{-1}$ from our work and $0.032\times10^{-18}ss^{-1}$ from Anderson's(Anderson 1993). As predicted by Rodolfi et al. (Ridolfi et al. 2017), the luminosity of M15C kept decreasing and the latest detection in our dataset is on December 20^{th}, 2022. We also detected M15I for one more time. The different barycentric spin periods indicate that this pulsar should locate in a binary system, manifesting itself as the exceptional one in such a core-collapsing GC.

Keywords: Radio pulsars(1353) — Globular star cluster(656) — Radio Astronomy(1338)

1. INTRODUCTION

Pulsars, rapidly rotating neutron stars, are usually searched with single-dish radio telescopes. Since the discovery of the first Globular Cluster (GC) pulsar (PSR B1821-24A Lyne et al. 1987), GCs have proven themselves as homes of millisecond binary pulsars. There are approximately 160 GCs in the Milky way (Forbes et al. 2018), and the surveys

[1] † panyu@cqupt.edu.cn

for pulsars in these clusters had been performed for decades. As of the submission of this letter, a total of 305 pulsars have been identified in 40 GCs[1].

M15 (NGC 7078) is a core-collapsed GC (Harris 1996). It stands out as one of the oldest ($\sim$ 12.0 Gyr) and most metal-poor Galactic GCs ([Fe/H] ~ -2.255), with a significant dense center (Sosin & King 1997; Koleva et al. 2008). Multi-decades observations are performed, successfully leading to profound results, e.g. M15A (Wolszczan et al. 1989), the double neutron star M15C, (Anderson et al. 1990; Deich & Kulkarni 1996). M15 has nine known pulsars in its vicinity, with eight discovered in the 1980s and 1990s with the Arecibo telescope. The M15I was found by Five-hundred-meter Aperture Spherical Radio Telescope (FAST, Nan et al. 2011) globular cluster pulsar survey[2].

M15A is a bright and isolated pulsar, boasting a notable flux density of approximately 0.2 ± 0.05 mJy at a frequency of 1415 MHz, discovered in 1989 (Wolszczan et al. 1989). M15B was reported one year later, with a period of approximately 56.13 ms, exhibiting a luminosity as twice as faint of M15A, despite still being considered a bright isolated pulsar (Anderson et al. 1990). M15C is in a highly eccentric binary system with an orbital period or 8 hours and an eccentricity of 0.68 (Anderson et al. 1990). Its component is a neutron star, too. It is similar to the well-known PSR 1913+16 system (Taylor & Weisberg 1982), and can be expected to provide tests for general relativity (Anderson et al. 1990). In previous studies, the brightness and polarimetric properties of M15C were reported, with a consistent decrease in flux and significant changes in the (polarised) pulse profile (Kirsten et al. 2014; Ridolfi et al. 2017). This suggests that M15C is precessing. Therefore, the continuous observation of M15C remains imperative, for understanding the effects of precession on the pulsar characteristics, the structure of M15C's emission beam, and the endeavor to detect potential signals originating from the companion of M15C.

After 2016, no follow-up observation for M15 was reported. The latest timing solutions for M15A, B, and C were in 2006, while the other pulsars' have remained unchanged since the 1990s (Anderson 1993; Jacoby et al. 2006).

There is a nearly thirty-year gap between the discovery of M15H and M15I. M15I was discovered in 2021 (Pan et al. 2021) and only been detected in one observation. It is still considered to be a new pulsar due to its appearances in the observation. According to simulations, M15 is possibly one of the GCs with the highest number of pulsars (Bagchi et al. 2011; Turk & Lorimer 2013). Therefore, it is believed that conducting a pulsar search within M15 is absolutely essential, and since the beginning of FAST GC pulsar suvery, M15 was one of the targets with highest priority. In this letter, we report the discoveries of three pulsars in M15, the re-detections of M15C and I, and updated timing solutions for M15A to H.

The structure of this letter is as follows: Section 2 presents the observation and data reduction, Section 3 shows the updated timing solution, the discussion is given in Section 4, and Section 5 is the summary.

2. OBSERVATION AND DATA REDUCTION

The observation of M15 with FAST started in October 2018. Those observations were done with the L-band 19-beam receiver which covers a frequency range of 1 to 1.5 GHz with 4096 channels, corresponding to a channel width of 0.122 MHz. All of the observational data were PSRFITS files in pulsar search mode and only the data from the central beam were used in this study. The beam size of the receiver is ~ 3 arcminutes. The core radius and half-light radius of M15 is 0.14 and 1.00 arcminute, respectively (Harris 1996). Thus, the central beam would be enough to cover the area where we would expect to detect signals from pulsars.

Aiming at finding new pulsars, during the six years from 2018 to 2023, a total of 18 observations were performed. Most of the observation were made with the TRACKING mode, while only one observation was made with the SNAPSHOT mode in order to cover the whole area of the GC.

To analyze the data, we employed the pulsar search code PRESTO (we employed the pulsar search code PRESTO Ransom 2011). We dedispersed data by using PREPSUBBAND in PRESTO. The dispersion measure (DM) range of known pulsars in M15 is $\sim$ 65.5 to 67.7 $\mathrm{pc\,cm^{-3}}$. Correspondingly, we dedispersed the data within a DM range of $63\,\mathrm{to}\,69\,\mathrm{pc\,cm^{-3}}$, with a DM step of 0.05 pc cm^{-3}. Subsequently, we applied REALFFT to transform the dedispersed time series to frequency domain and then applied ACCELSEARCH for periodic signal search. Because the signal of binary M15C is one of our primary targets, the acceleration search parameter ZMAX is set to be 100 and the number of harmonics to sum was 32. The search results were sifted by ACCEL_SIFT.PY and according to the DM values and

[1] Pulsars in globular clusters https://www3.mpifr-bonn.mpg.de/staff/pfreire/GCpsr.html

[2] GC-FANS (Globular Cluster FAST: A Neutron-star Survey,)https://fast.bao.ac.cn/cms/article/65/

periods of the candidates, the data were fold with PREPFOLD from PRESTO. To save time, we used RPPPS 4.0[3] to run these PRESTO routines in parallel.

In a previous study, Verbunt et al. explained the possibility of presence of slow pulsars in core-collapsed GC (Verbunt & Freire 2014). As an example, a slow pulsar with a ∼2.4 s period was found in the core-collapsed GC NGC 6624 (Abbate et al. 2022). Being a core-collapsed GC, too, M15 may also contain long-period pulsars. It is worthy noting that M15A is an isolated pulsar with a period longer than 100 ms (110.6 ms Wolszczan et al. 1989), indicating that applying Fast Fold Algorithm (FFA) on M15 data is possibly and potentially suitable to find new long period pulsars. The FFA code Riptide-FFA[4] was used in the data processing. In terms of FFA search settings, we followed the examples provided on the Riptide-FFA website[5]. The period ranges used for our search are three segemts, being the short period search range of 0.2 s to 1 s, the medium range search of 1 s to 5 s, and the long one from 5 s to 180 s.

The search results from both PRESTO and Riptide-FFA are all presented in Table.1.

Table 1. M15 pulsar detections for known pulsars. The "$\surd$" stand for those detections found in search results, "$\star$" are for those not detected in search results but can be found by folding with timing solutions. For new pulsars, M15J was detected in 11 out of 18 observations. For M15K and L, they are bright enough to be detected in observations longer than ∼1 hour. Their detections depend on the situation of radio frequency interference masking. Thus, we did not put detection information of these new pulsars here.

Obs Date	M15A	M15B	M15C	M15D	M15E	M15F	M15G	M15H	M15I
2018.10.13	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		$\star$	
2018.11.17	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\star$		$\star$	
2019.04.25	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$		$\surd$	
2019.08.18	$\surd$	$\surd$	$\star$	$\surd$	$\surd$			$\star$	
2019.11.09	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$		$\surd$	
2019.12.14	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$		$\star$	
2020.08.30	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$		$\star$	
2020.09.02	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$		$\star$	
2020.09.22	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$		$\surd$	$\surd$
2020.09.25	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$		$\star$	
2020.12.21	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$		$\surd$	
2021.03.09	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$	$\star$	$\star$	
2022.01.02	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$	$\surd$	$\star$	
2022.07.07	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$	$\star$	$\star$	
2022.11.19	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$	$\star$	$\surd$	
2022.12.20	$\surd$	$\surd$	$\star$	$\surd$	$\surd$	$\surd$	$\star$	$\surd$	
2023.01.20	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$	$\star$	$\surd$	$\surd$
2023.02.20	$\surd$	$\surd$		$\surd$	$\surd$	$\surd$		$\star$	
Total	18	18	12	18	18	17	6	18	2

3. RESULTS

A total of 18 observations were carried out from October 2018 (MJD 58404) to February 2023 (MJD 59995), spanning 1591 days. Due to variations in observation scheduling, the observations lasted for half an hour to five hours.

3.1. *New Pulsars*

From the results obtained from Riptide-FFA, a harmonically related signal with a signal-to-noise ratio (SNR) of 9.2 was detected in the data recorded on December 14, 2019. Its pulse profile has 10 peaks, and the signal has a period of 110.83 ms, with the optimal SNR at a DM of 66.40 $\mathrm{pc\,cm^{-3}}$. Subsequent investigations confirmed that this signal

[3] https://github.com/qianlivan/RPPPS),Yu et al. (2020)

[4] https://riptide-ffa.readthedocs.io/en/latest/

[5] Riptide-FFAhttps://riptide-ffa.readthedocs.io/en/latest/pipeline.html#number-of-parallel-processes

was the tenth harmonic of a new pulsar's signal, leading to the discovery of M15J. Then, such signals were successfully detected in multiple observations. With more data recently obtained by FAST, the phase-connected timing solution (See Table.2) was obtained. M15J is an isolated pulsar with a spinning period of 11.84 ms and with a DM value of 66.68 pc cm^{-3}.

From the observation of December 21, 2020, two long-period pulsars, namely M15K and M15L, were detected by Riptide-FFA. The signals of M15K and M15L have periods of approximately 1920 ms and 3961 ms, respectively, both with DM values of 65.00 $\mathrm{pc\,cm^{-3}}$ for the best SNR. Due to the Radio Frequency Interferences (RFIs), their SNR is very limited. Thus, we only obtained timing solution with JUMPs (See Figure.3) and only the spinning periods were fitted (Table.2). In order to detect them for more times, more weak RFIs should be masked and removed from the data.

3.2. *Known Pulsars*

M15C appeared for three times in the search results. To obtain as many signals as possible, we also used the ephemeris from the ATNF Pulsar Catalogue [6] (Manchester et al. 2005). Seen from the results, this ephemeris is no longer accurate enough for our FAST data, but we were still able to identify the signals of M15C in folding results and successfully obtained its timing solution. The fitted orbital period, projected semi-major axis, epoch of periastron, eccentricity, and longitude of periastron are 0.3352820162(3), 2.51842(1), 50000.064743(8), 0.681404(9) and 345.312(2), being consistent with previous results (e.g. Anderson 1993).

For the other pulsars in M15, we detected all of them. Their detection rates can be found in Table.1 We have obtained the fully phase-connected timing solution for M15A, B, D, E, F, H (See Table.2, ephemeris from ATNF Pulsar Catalogue were also used for the timing of M15G and H). For M15G, we can not remove all the JUMPs due to that it is too faint and only detected for 6 time. The timing solutions for M15A, B, D, E, and H are basically consistent with previous studies, while M15F exhibits an offset for P1, which will be discussed in an upcoming chapter.

The most recently discovered pulsar M15I was detected for one more time on December 20^{th}, 2022 (MJD 59933). In comparison to its discovery and confirmation observation on September 22^{nd} 2020, the signal of M15I on December 20^{th} 2022 matched well both in the spinning period and the shape of the pulse profile (See Fig.1 1). From the observation on September 22, 2020, its barycentric period and the acceleation inferred from the period derivative are 5.1221966(4) ms and -0.011(11) m s^{-2}, respectively, while they are 5.1221974(2) ms and 0.0071(36) m s^{-2}, respectively, from the observation on December 20^{th} 2022. These suggest that M15I should be in a binary system. Inferred from the efficiency of acceleration search (Ransom 2001), if M15I is a binary, the orbital period should be longer than 50 hours.

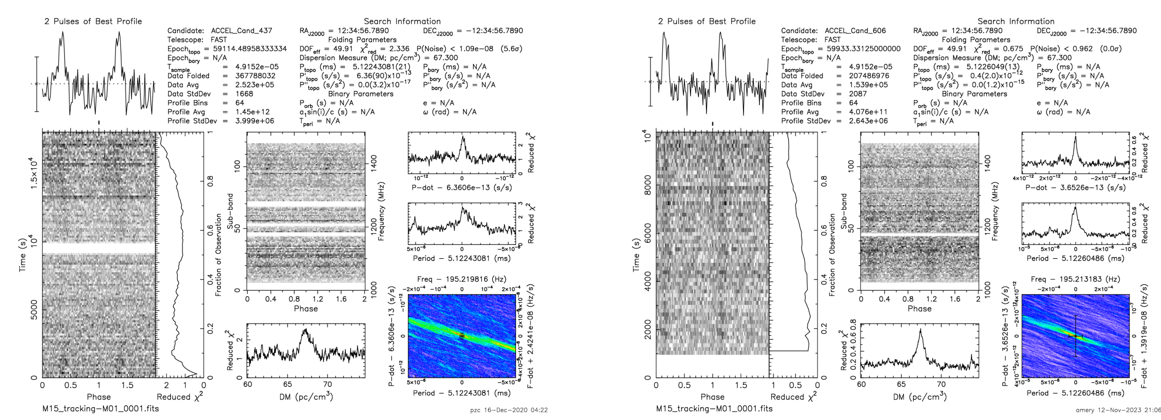

Figure 1. M15I detection, on MJD 59144 (left) and MJD 59933 (right)

4. DISCUSSION

[6] psrcat, https://www.atnf.csiro.au/research/pulsar/psrcat/

Table 2. Parameters for pulsars in GC M15, timing positions for M15G, K, and L was not obtained, the position of them is M15C center

Pulsar	2129+1210A	2129+1210B	2129+1210C	2129+1210D
Right Ascension, α (J2000)	21:29:58.24642(4)	21:29:58.6280(1)	21:30:01.2031(4)	21:29:58.2692(1)
Declination, δ (J2000)	12:10:01.172(1)	12:10:00.283(7)	112:10:38.19(2)	12:09:59.645(2)
Spin Frequency, f (s^{-1})	9.0363060726718(5)	17.814819156216(5)	32.7554227003(4)	208.21173107090(3)
1st Spin Frequency derivative, $\dot{f}$ (Hz s^{-2})	$1.713989(9) \times 10^{-15}$	$-3.0295(6) \times 10^{-15}$	$-5.3523(5) \times 10^{-15}$	$4.63917(4) \times 10^{-14}$
Reference Epoch (MJD)	58598.012893	58404.479166	58404.483246	58831.3534
Start of Timing Data (MJD)	58404.479	58404.479	58404.479	58404.479
End of Timing Data (MJD)	59247.313	59964.318	59964.318	59964.329
Dispersion Measure, DM (pc cm^{-3})	67.226(1)	67.731(6)	67.10	67.277(2)
Solar System Ephemeris	DE421	DE421	DE421	DE421
Number of TOAs	219	252	109	248
Residuals RMS (μs)	27.484	71.833	99.009	38.475
PULSAR	2129+1210E	2129+1210F	2129+1210G	2129+1210H
Right Ascension, α (J2000)	21:29:58.18447(4)	21:29:57.1783(1)	21:29:58.33	21:29:58.1828(3)
Declination, δ (J2000)	12:10:08.508(1)	12:10:02.818(2)	12:10:01.20	12:09:59.291(5)
Spin Frequency, f (s^{-1})	214.987399714593(8)	248.32119058101(2)	26.553253(6)	148.2932725188(7)
1st Spin Frequency derivative, $\dot{f}$ (Hz s^{-2})	$-8.5721(1) \times 10^{-15}$	$-1.6719(4) \times 10^{-15}$	......	$-4.702(7) \times 10^{-16}$
Reference Epoch (MJD)	59883.353	59933.331	47632.520	47632.520
Start of Timing Data (MJD)	58404.483	59404.483	59282.167	58796.482
End of Timing Data (MJD)	59995.172	59995.172	59964.320	59964.324
Dispersion Measure, DM (pc cm^{-3})	66.586(1)	65.597(2)	64.40	67.117(5)
Solar System Ephemeris	DE421	DE421	DE421	DE421
Number of TOAs	247	165	15	167
Residuals RMS (μs)	17.758	22.171	194.011	69.213
PULSAR	2129+1210J	2129+1210K	2129+1210L	
Right Ascension, α (J2000)	21:29:58.4119(5)	21:29:58.33	21:29:58.33	
Declination, δ (J2000)	12:10:16.00 (1)	12:10:01.20	12:10:01.20	
Spin Frequency, f (s^{-1})	84.4417459611(1)	0.5185510(3)	0.2524818(2)	
1st Spin Frequency derivative, $\dot{f}$ (Hz s^{-2})	$-1.451(2) \times 10^{-15}$	......	....	
Reference Epoch (MJD)	59995.156	58204.256	59204.256900	
Start of Timing Data (MJD)	58796.482	58831.412	59091.639	
End of Timing Data (MJD)	59995.191	59902.507	59581.331	
Dispersion Measure, DM (pc cm^{-3})	66.688(8)	68.01	67.10	
Solar System Ephemeris	DE421	DE421	DE421	
Number of TOAs	127	34	78	
Residuals RMS (μs)	60.973	6997.640	70771.425	

In Figure.2, the timing positions and Chandra X-ray sources in M15 are presented as the observational coordinates. The positions of M15G is from Anderson's paper (Anderson 1993). Among those pulsars, none of them has X-ray counterpart.

In Figure.3, the timing residuals for all pulsars in M15 is presented. Due to limitations in data quality, not all observational data were utilized. The pulse profiles of M15I, K, and L are from only one observation, because of their limited detections and significant interference.

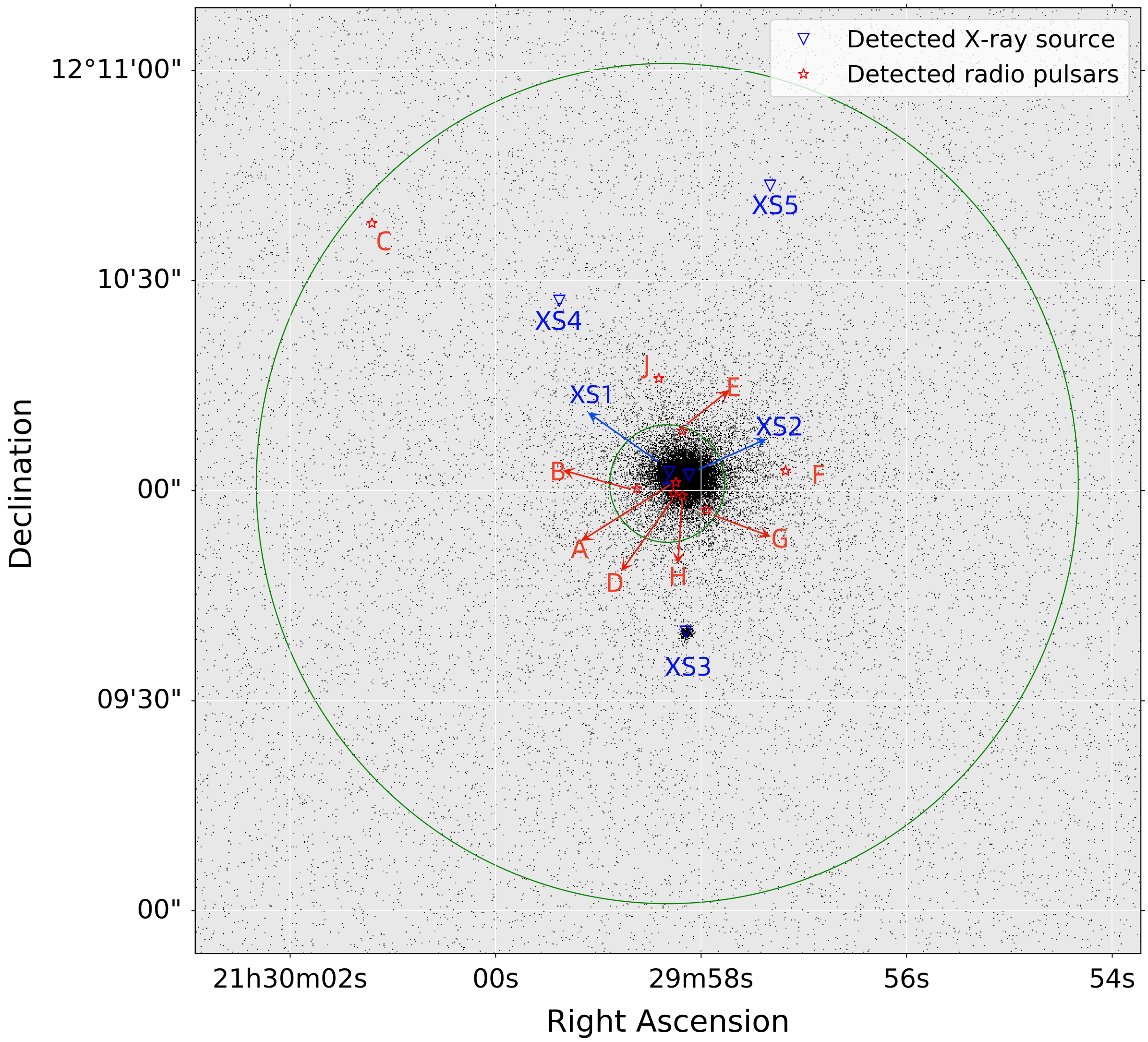

Figure 2. Pulsar positions and X-ray source positions in M15

4.1. *Detection Rates*

The fluxes of M15A, B, D, and E are likely to remain stable. These four pulsars are bright enough to be detected even from the half-an-hour data. Their timing solutions are consistent with those from previous studies (Anderson 1993). The timing result of M15C will be duscussed in the next subsection. Our timing solution of M15F shows different from Anderson's. The P1 from our timing is approximately $0.027 \times 10^{-18} ss^{-1}$ while $0.032 \times 10^{-18} ss^{-1}$ from Anderson's work (Anderson 1993). M15G, which was redetected only once in FAST data of January 02, 2022 (Pan et al. 2021), now has 6 detections in total. More observations are needed to obtain its position and spinning frequency derivative. The M15H were searched for 7 times among the 18 observations (39%). While folded with timing solution, its signal appears in every observation. It seems that both the variation of flux and the scintillation are reasons for its detection. The M15I was detected for one more time and will be mentioned later.

M15J is an isolated millisecond pulsar (MSP). It was detected for 11 times (detection rate 61%). For M15K, and L, due to RFIs, both of them can be seen in every observation, while only very limited observations (8 times for M15K, 4 times for M15L) can be used to extract TOAs. Thus, we only fitted the spinning frequencies, F0.

4.2. *The Double Neutron Star M15C*

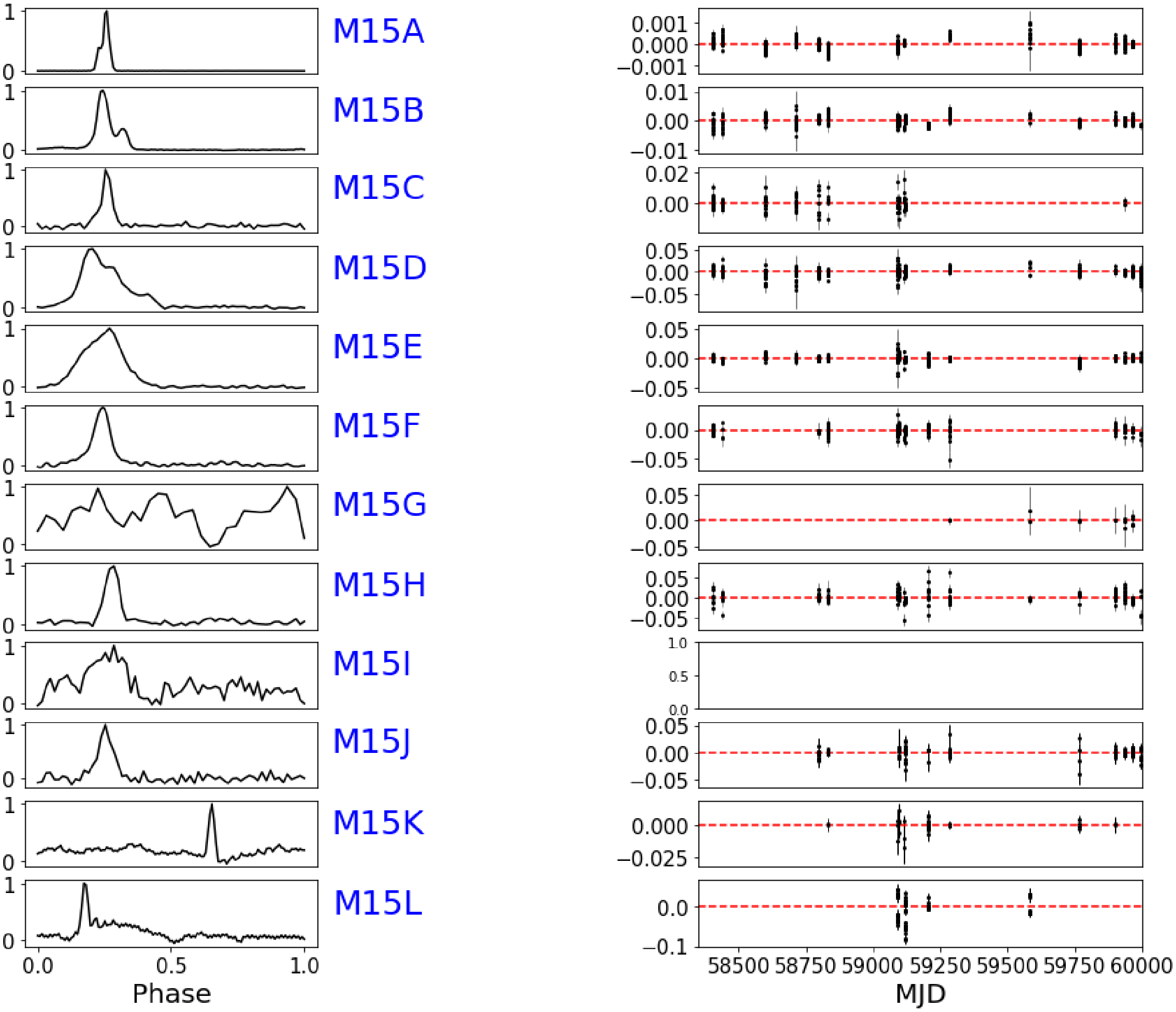

Figure 3. Average profile and timing reseduals for pulsars in M15

M15C is in a well-studied pulsar-neutron star system. The mass of its companion, orbital parameters have all been preciously obtained in previous studies (Anderson 1993; Deich & Kulkarni 1996; Jacoby et al. 2006). Compared with the results in 2014, M15C displayed much higher linear polarization in 2016 (Ridolfi et al. (2017)). It is predicted that the signal of M15C will become fainter and finally disappears between 2041 and 2053. In our dataset, the most recent detection to M15C was in December 20$^{\text{th}}$, 2022. The duration of this observation is about three hours. The SNR of the M15C signal remained low (about 6.9), indicating that it is almost outside of our line of sight. After this observation, no signals from M15C were detected till now (e.g. 3-hour observation on 2023.01.20).

In order for polarization analysis, the data should be recorded in four polarizations and with noise diode on at the beginning. We only have three such observations. Luckily, in the data obtained on December 14$^{\text{th}}$, 2019, M15C was strong enough. It is consistent with the previous study that M15C continues to exhibit a high linear polarization (see Figure 4).

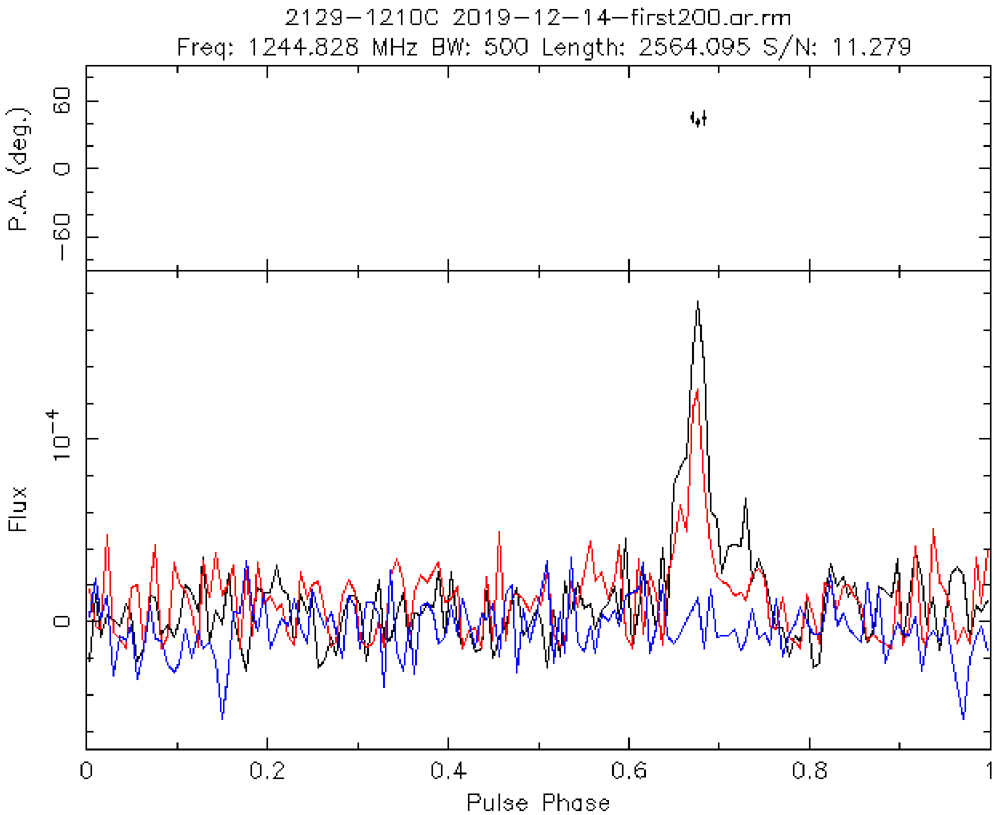

Figure 4. M15C polarization status in 2019, shows it's still highly linear polarized

4.3. *Slow Pulsars M15K and M15L*

In previous surveys, there were two pulsars in GCs that have been identified with periods more than one second: B1718-19 (1004 ms, NGC 6342A, Wijers & Paczynski 1993) and J1823-3022 (2497 ms, may be in NGC 6624, Abbate et al. 2022). B1718-19A is in a binary system with a low-mass non-degenerate star as its companion, associated with the core-collapsed GC NGC 6342. Due to the DM difference ($\sim$ 9.3 pc cm^{-3} from the average DM for known pulsars) and a offset of 3 arcminutes to the GC center, J1823-3022 may not associated with the core-collapsed GC NGC 6624.

The spinning periods of M15K and L are 1.9 s and 3.9 s, respectively, ranking 3$^{\rm rd}$ and 1$^{\rm st}$ among all the GC pulsars. At present, the properties of M15K and M15L, such as their positions and P-dot, remain unknown. The beam size of FAST 19 beam receiver is 3 arcminutes. Although the precise positions of these two pulsars remain unknown at present, detection of M15K and M15L in the center beam indicates that they are not too far away from the core of M15. The absence of those crucial information currently hinders our ability to determine whether they are young or recycled pulsars, and if they are associated with M15. Their detections and TOAs are severely affected by significant RFIs. Eliminating these RFIs to enhance the signal quality and accomplishing their timing solution are the primary objectives of our future works.

A plausible conjecture for the presence of those two pulsars is that they may be partially recycled: due to the large recoils resulting from binary interactions that occurred during their disruption, recycling pulsars in binary systems were ejected from the center and had insufficient time to sink back to the central region.

4.4. *Confirmation of M15I*

M15I is a millisecond pulsar that had been detected only once and confirmed in the same observation. Normally, a pulsar was confirmed until one more detection in another observation. During the observation of M15 made on September 22, 2020, the FAST telescope experienced a mechanical issue during the observation and caused it not to point at M15 for approximately 7000 seconds. The signal of M15I was detected in this observation and disappeared

in such 7000-second segment. This is agreed with that the signal was from the sky and entered the receiver in the direction of M15. When the pointing is changed, the signal disappeared accordingly. Thus, M15I was detected and confirmed in one observation. Similar method was suggested to be used to detect and confirm highly nulling pulsars, named spatial modulation search (Qian & Pan 2021), while as the first example, M15I needs one more detection to prove that the pulsar indeed exist and the method works.

With ACCELSEARCH from PRESTO, the M15I were detected again with the ZMAX value of 100 on the data dedisperion with a DM value of 67.6 pc cm^{-3}. With a very small but detectable acceleration, it is an exceptional pulsar in such core-collapsed GC. The reason of the variation of its flux is unknown while more observation should be performed to get its timing solution.

5. CONCLUSION

In this paper, we presented our studies on the pulsars of the core-collapsed GC M15. The conclusions are as follows:

1, Observations to M15 had been implemented with FAST since 2018, resulting in re-detection for all the 9 previously known pulsars and the discovery of M15J, K, and L.

2, Updated timing solutions for M15A, B, D, E, and H are consistent with previous ones (Anderson 1993), while the timing results of M15F shows smaller P1.

3, M15C, the double neutron star binary system, was detectable by FAST until December 20$^{\mathrm{th}}$, 2022. Its flux kept decreasing. This may be the result of precession. Being consistent with the result in 2016, its pulse profile is still highly linear polarized in the observation taken in December 14$^{\mathrm{th}}$, 2019. As it disappears in FAST data, it may be possible to receive the signal from the companion.

4, M15I was detected one more time on December 14$^{\mathrm{th}}$, 2022. It should be a binary in a wide orbit.

5, Newly discovered pulsar M15J is an isolated pulsar, with a spinning period of 11.84 ms and the DM value of 66.68 pc cm^{-3}.

6, As two long period pulsars, M15K and L have spinning periods of 1.98 s and 3.61 s. M15L is the GC pulsar with the longest spinning period now known. Due to the RFIs, it is not easy to obtain their phase-connected timing solutions. Their spinning frequency derivatives could be the key to determine if they are recycled.

REFERENCES

Abbate, F., Ridolfi, A., Barr, E. D., et al. 2022, MNRAS, 513, 2292, doi: 10.1093/mnras/stac1041

Anderson, S. B. 1993, PhD thesis, California Institute of Technology

Anderson, S. B., Gorham, P. W., Kulkarni, S. R., Prince, T. A., & Wolszczan, A. 1990, Nature, 346, 42, doi: 10.1038/346042a0

Bagchi, M., Lorimer, D. R., & Chennamangalam, J. 2011, MNRAS, 418, 477, doi: 10.1111/j.1365-2966.2011.19498.x

Deich, W., & Kulkarni, S. 1996, in Symposium-International Astronomical Union, Vol. 165, Cambridge University Press, 279–285

Forbes, D. A., Bastian, N., Gieles, M., et al. 2018, Proceedings of the Royal Society of London Series A, 474, 20170616, doi: 10.1098/rspa.2017.0616

Harris, W. E. 1996, AJ, 112, 1487, doi: 10.1086/118116

Jacoby, B. A., Cameron, P. B., Jenet, F. A., et al. 2006, ApJL, 644, L113, doi: 10.1086/505742

Kirsten, F., Vlemmings, W., Freire, P., et al. 2014, Astronomy & Astrophysics, 565, A43

Koleva, M., Prugniel, P., Ocvirk, P., Le Borgne, D., & Soubiran, C. 2008, MNRAS, 385, 1998, doi: 10.1111/j.1365-2966.2008.12908.x

Lyne, A. G., Brinklow, A., Middleditch, J., Kulkarni, S. R., & Backer, D. C. 1987, Nature, 328, 399, doi: 10.1038/328399a0

Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993, doi: 10.1086/428488

Nan, R., Li, D., Jin, C., et al. 2011, International Journal of Modern Physics D, 20, 989, doi: 10.1142/S0218271811019335

Pan, Z., Qian, L., Ma, X., et al. 2021, ApJL, 915, L28, doi: 10.3847/2041-8213/ac0bbd

Qian, L., & Pan, Z.-C. 2021, Research in Astronomy and Astrophysics, 21, 185, doi: 10.1088/1674-4527/21/8/185

Ransom, S. 2011, PRESTO: PulsaR Exploration and Search TOolkit, Astrophysics Source Code Library, record ascl:1107.017. http://ascl.net/1107.017

Ransom, S. M. 2001, PhD thesis, Harvard University, Massachusetts

Ridolfi, A., Freire, P., Kramer, M., et al. 2017, Proceedings of the International Astronomical Union, 13, 251

Sosin, C., & King, I. R. 1997, AJ, 113, 1328, doi: 10.1086/118346

Taylor, J. H., & Weisberg, J. M. 1982, ApJ, 253, 908, doi: 10.1086/159690

Turk, P. J., & Lorimer, D. R. 2013, MNRAS, 436, 3720, doi: 10.1093/mnras/stt1850

Verbunt, F., & Freire, P. C. C. 2014, A&A, 561, A11, doi: 10.1051/0004-6361/201321177

Wijers, R. A. M. J., & Paczynski, B. 1993, ApJL, 415, L115, doi: 10.1086/187046

Wolszczan, A., Kulkarni, S. R., Middleditch, J., et al. 1989, Nature, 337, 531, doi: 10.1038/337531a0

Yu, Q.-Y., Pan, Z.-C., Qian, L., et al. 2020, Research in Astronomy and Astrophysics, 20, 091, doi: 10.1088/1674-4527/20/6/91